

CHAPTER 7

POLYMERS AND ITS PROPERTIES

Introduction

In chapter 1, we classified materials into metals, ceramics and polymers. Here we discuss the material carbon. Carbon has various polymorphic forms such as graphite, diamond, graphene and fullerenes. This group of materials does not fall within any of the above class. Graphite is sometimes classified as ceramics. The diamond, one of the polymorphs of carbon exhibits the structure of zinc blende which is a crystal. Here we confine our attention to the structure and characteristics of different polymorphs of carbon.

Diamond

Diamond is one of the polymorphic forms of carbon at room temperature and atmospheric pressure. Its crystal structure is similar to that of zinc sulphide in which carbon atoms occupy all positions (both Zn and S). The unit cell of diamond is shown in figure 7.1. In this structure each carbon atom bonds to four other carbon atoms and these bonds are totally covalent. This is called the diamond cubic crystal structure. Germanium, silicon and graytin show the same crystal structure below 13°C.

Physical properties of diamond

1. It is the hardest known material.

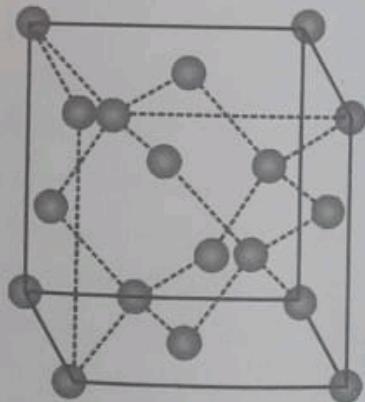


Figure 7.1: A unit cell for the diamond cubic crystal structure

2. It has very low electrical conductivity.

The above two properties are due to its crystal structure and the strong interatomic covalent bonds.

3. It has an unusually high thermal conductivity and is optically transparent in the visible and infrared regions of electromagnetic spectrum.
4. It has a high refractive index of refraction.

Uses

1. Diamonds are utilised to grind or cut other soft materials.
Example is glass cutter.
2. Relatively large diamond single crystals are used as gem stones.

Synthetic diamonds production techniques have been developed in the industry. Most of the diamonds available in the market are man-made ones.

Recently techniques to produce diamond thin films have been developed. The very interesting thing is that the optical properties of diamond films approach those of the bulk diamond material. These properties enabled us to produce new and better products. For example, the surfaces of drills, dies, bearings, knives and other tools have been coated with diamond films to increase surface hardness. Some lenses have been made stronger while remaining transparent by the application of diamond coatings. Diamond coatings also have been applied to loud speaker tweeters and to high precision micrometers. Another very important application of diamond films is to coat on the surface of machine components such as gears, optical recording heads and disks.

Graphite

Graphite is another polymorphic form of carbon. Its crystal structure is distinctly different from that of diamond and is also more stable than diamond at ambient temperature and pressure.

The graphite structure composed of layers of hexagonally arranged carbon atoms. Within the layers each carbon atom is bonded to three coplanar neighbour atoms by strong covalent bonds. The fourth bonding electron participates in a weak vander Waals types of bond between the layers.

Properties

1. As a consequence of these weak interplanar bonds, interplanar cleavage is facile which gives rise to the excellent lubricative properties of graphite.
2. The electrical conductivity is relatively high in crystallographic directions parallel to the hexagonal sheets.
3. Another important property of graphite is its high strength and chemical stability at elevated temperatures.
4. Graphite has high thermal conductivity, low coefficient of thermal expansion and high resistance to thermal shock.

Uses

1. It is used as heating elements for electric furnaces, as electrodes for arc welding
2. Graphites are used in casting molds for metal alloys and ceramics.
3. They are used in high temperature refractories.
4. Graphites are also used for electrical contacts, such as electrodes in batteries.

The structure of graphite is given above.

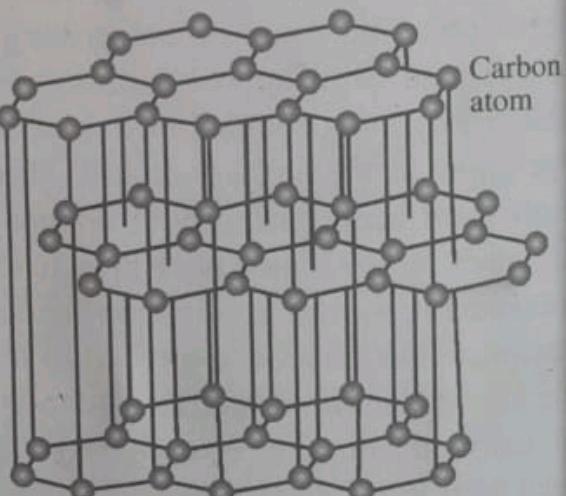


Figure 7.2: The structure of graphite

Fullerenes

Harry Kroto and Richard Smalley around 1980 discovered a new class of carbon material called carbon 60 (C_{60}). It is another polymorphic form of carbon. It exists in discrete molecular form and consists of a hollow spherical cluster of sixty carbon atoms; a single molecule is denoted by C_{60} . Each molecule is composed of groups of carbon atoms that are bonded to one another to form both hexagon (six carbon atoms) and pentagon (five carbon atoms) geometrical configurations. One such molecule is shown in figure 7.3.

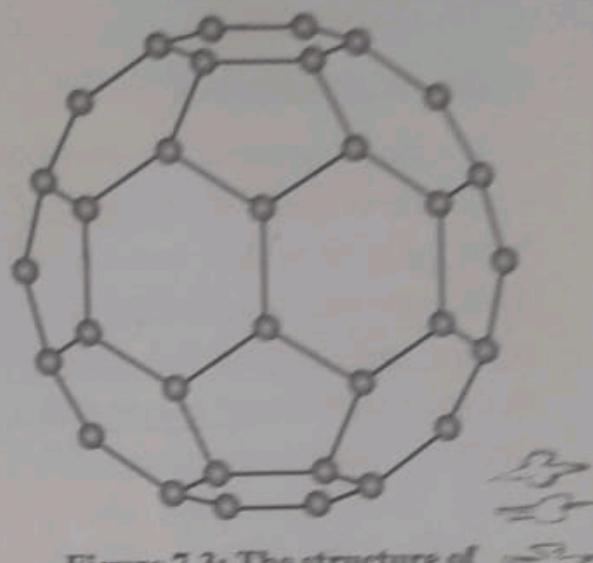


Figure 7.3: The structure of C_{60} molecule

A single C_{60} molecule altogether consists of 20 hexagons and 12 pentagons, which are arrayed such that no two pentagons share a common side. Thus the surface of this molecule exhibits the symmetry of a soccer ball. The material composed of C_{60} molecules is known as buckminsterfullerene, named in honour of R. Buckminster Fuller who invented the geodesic dome; each C_{60} is simply a molecular replication of such a dome which is often referred to as "buckyball" for short. The term fullerene is used to denote the class of materials that are composed of this type of molecule. The C_{60} units form a crystalline structure and pack together in a face-centred cubic array. The fullerene material is electrically insulating. However with proper impurity additions, it can be made highly conductive and semiconducting. Presently, we know that C_{60} doped with alkali metals become superconducting at $T_c = 5K$.

At present many methods are available to prepare C_{60} moles in large quantities, so the study of this molecular form of carbon is

advancing in many areas. Any research work on fullerene has got immense scope and potential in the field of nanotechnology. They find use in catalytic chemistry, biomolecular recognition, as molecular sieves, nanoreactors and also as inhibitors to the activity of HIV virus, etc.

Carbon nanotubes

Carbon nanotube is another molecular form of carbon. Its structure consists of a single sheet of graphite rolled into a tube, both ends of which are cupped with C_{60} fullerene hemispheres. This structure is schematically represented in figure 7.4. Since the tube diameters are of the order of nanometre (i.e. 100 nm or less), this carbon tube is called nanotubes. Each nanotube is a single molecule composed of millions of atoms; the length of the molecule is 1000 times greater than its diameter.

- Nanotubes have some unique and technologically promising properties.

Properties

1. They are extremely strong stiff and relatively ductile.
2. The tensile strengths of single walled nanotubes ranges from 50 to 200 GPa, which is greater than that of carbon fibres.
3. This is the strongest known material.
4. The elastic modulus values are of the order of terapascal (10^{12} Pa) relatively.
5. Nanotubes have low densities.

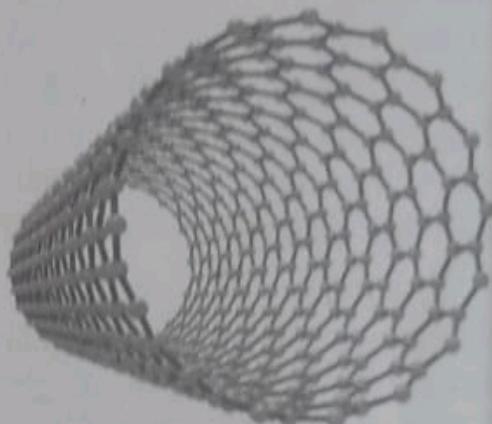


Figure 7.4: The structure of a carbon nanotube

Uses

1. Carbon nanotubes as reinforcement in composite materials.
2. Since the nanotubes behave electrically as either a metal or a semiconductor depending upon the impurity atoms added, they have been used in flat panel and full colour displays of TVs and monitors of computers. Carbon nanotubes in these are field emitters.
3. They are cheaper to produce and require only lower power than CRT and liquid displays.
4. Carbon nanotubes can find applications in the fabrications of diodes and transistors, will result in nanoelectronic devices.

There is a scope of wide applications in different fields such as electronics in terms of thin films, electronic devices like MOSFET, JFET and in electrical ceramics.

The structure of polymers

Introduction

We are familiar with so many materials such as wood, rubber, cotton, wool, leather and silk; they are all naturally occurring polymers, proteins, enzymes, starches and cellulose are important in biological and physiological processes in plants and animals these are also natural polymers. The molecular structures of this group of material have been studied and researchers developed synthetic polymers from small organic molecules such as plastics, rubbers and fibre materials. The synthetic polymers can be produced inexpensively and their properties are superior to their natural counterparts. The properties of polymers related to their structure of the materials. In this section we deal with the relationship between structure and some of the physical and chemical properties.

Hydrocarbon molecules

Most of the polymers are organic in origin and are hydrocarbons

i.e. they are composed of hydrogen and carbon. In hydrocarbons intramolecular bonds are covalent. Each carbon atom has four electrons that may participate in covalent bonding, whereas every hydrogen atom has only one bonding electron. A single covalent bond exists when each of the two bonding atoms contributes one electron as shown in figure 7.5 for methane. Double and triple bonds between two carbon atoms involve the sharing of two or three pairs of electrons, respectively. For example in ethylene (C_2H_4) has two carbon atoms are doubly bonded and each is single bonded to two hydrogen atoms.

Methane (CH_4) ethylene (C_2H_4) and acetylene (C_2H_2) are represented by the structural formula as shown below.

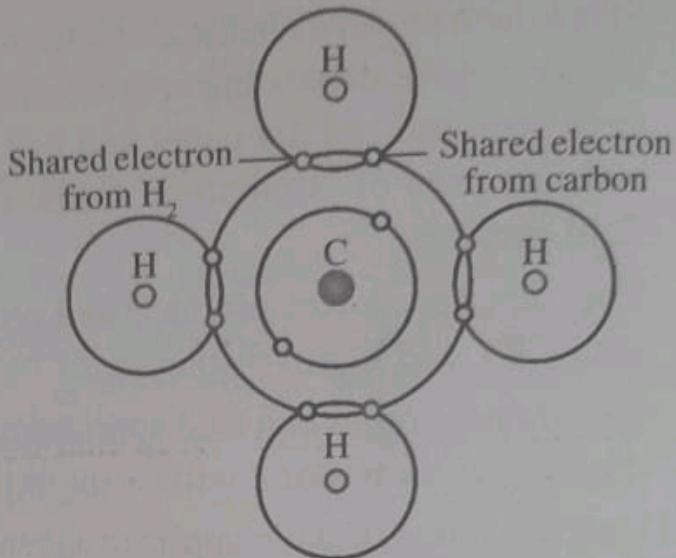


Figure 7.5: Schematic representation of covalent bonding in a molecule of methane (CH_4)

1. Methane CH_4 , $\begin{array}{c} H \\ | \\ H-C-H \\ | \\ H \end{array}$ having four single bonds

2. Ethylene C_2H_4 , $\begin{array}{cc} H & H \\ | & | \\ C = C \\ | & | \\ H & H \end{array}$ Four single bonds are one double bond.

3. Acetylene C_2H_2 , $H-C\equiv C-H$ Two single bonds and one triple bond.

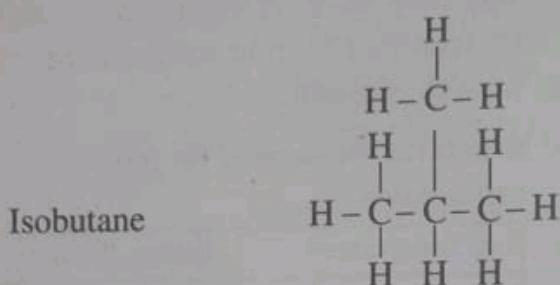
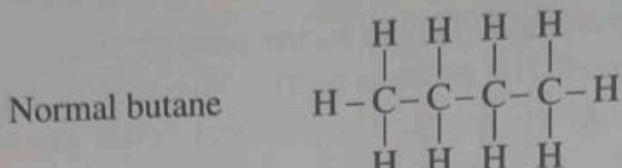
Molecules that have double and triple bonds are termed unsaturated and for saturated hydrocarbons have all single bonds.

Some of the hydrocarbons belong to the paraffin family are methane (CH_4), ethane (C_2H_6), propane (C_3H_8) and butane (C_4H_{10}), whose structures are given below. The covalent bonds in each molecule are strong but only weak hydrogen vander waals bonds exist between molecules, thus they have relatively low melting and boiling points. It is also seen that boiling temperatures rise with increasing molecular weight. See table 7.1.

Table 7.1: Molecular structures for some of the paraffin compounds.

Name	Composition	Structure	Boiling Point (°C)
Methane	CH_4	$\begin{array}{c} H \\ \\ H-C-H \\ \\ H \end{array}$	-164
Ethane	C_2H_6	$\begin{array}{cc} H & H \\ & \\ H-C-C-H \\ & \\ H & H \end{array}$	-88.6
Propane	C_3H_8	$\begin{array}{ccc} H & H & H \\ & & \\ H-C-C-C-H \\ & & \\ H & H & H \end{array}$	-42.1
Butane	C_4H_{10}		-0.5
Pentane	C_5H_{12}		36.1
Hexane	C_6H_{14}		69.0

Hydrocarbon compounds with the same composition may have different atomic arrangements, a phenomena termed as isomers. For example there are two isomers for butane. They are normal butane and isobutane. Their structures are given below.



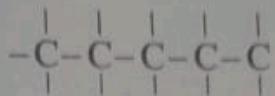
Some of the physical properties of hydrocarbons will depend upon the isomeric state. For example, the boiling temperatures for normal butane and isobutane are -0.5 and -12.3°C respectively.

Polymer molecules

The term polymer means many parts. Poly means many and mer is a Greek word meaning part. The term monomer refers to the small molecule from which a polymer is synthesised.

Polymer molecules are gigantic molecules in comparison to the hydrocarbons. It is because of large size of polymer molecules they are often referred to as macromolecules, within each molecule, the atoms are bound together by covalent bonds.

For carbon chain polymers, the back bone of each chain is a string of carbon atoms. Many times each carbon atom singly bonds to two adjacent carbon atoms on either side, represented schematically as follows (Two dimension):

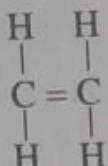


Each of the two remaining valence electrons of every carbon atom may be involved in side bonding with atoms or radicals that are positioned adjacent to the chain. It may also be noted that both chain and side double bonds are also possible.

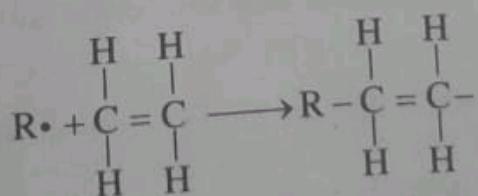
Formation of polymer molecules

When a monomer is reacted under proper conditions with an initiator or a catalyst, a polymer molecule is formed.

For example ethylene (C_2H_4) is monomer and is a gas at ambient temperature and pressure. Its molecular structure is

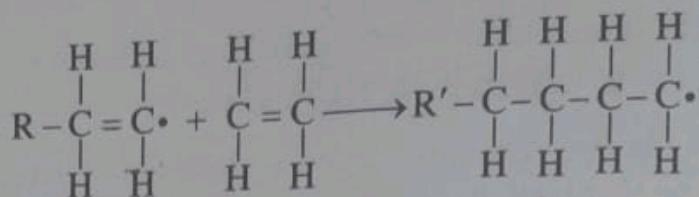


when this ethylene gas is reacted under appropriate conditions with a catalyst R, it will transform to polyethylene (PE), which is a solid polymeric material. The process begins when an active centre is formed by the reaction between catalyst species (R) and ethylene monomer. This is represented as follows:



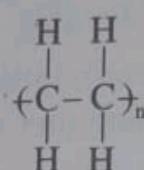
The active centre is denoted by $(R \cdot)$.

By the sequential addition of monomer to this active growing chain, a polymer is formed. It is represented as follows:

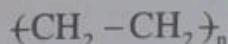


Repeating we get polyethylene molecule.

The polyethylene structure can also be represented as



or



where n indicates the number of times the monomer repeats.

In a three dimensional model representation carbon atoms form zigzag pattern shown in figure 7.6.

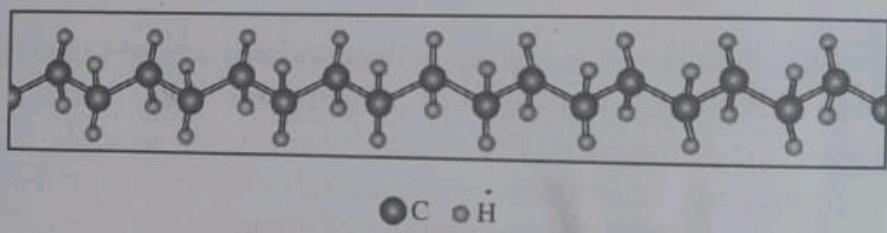
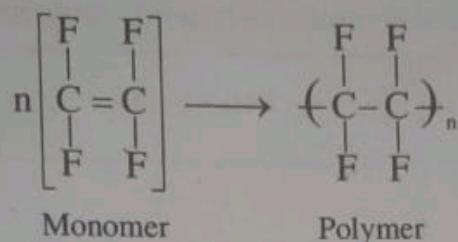


Figure 7.6: Zigzag back bone structure of polyethylene

It may also be noted that the angle between the singly bonded carbon atom is not actually 180° as we have shown, $\text{---} \overset{180^\circ}{\text{C}} \text{---}$, but rather close to 109° .

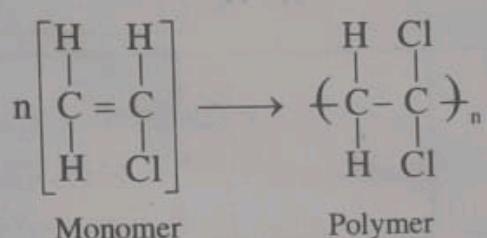
Other examples

1. Tetrafluoroethylene $\text{CF}_2 = \text{CF}_2$ is a monomer. This can polymerise to give polytetrafluoroethylene (PTFE) called teflon (trade name). Its structure is represented as follows:



2. Vinyl chloride $\text{CH}_2 = \text{CHCl}$ is a monomer. It is a variant of ethylene C_2H_4 in which one of the hydrogen atom is replaced by chlorine atom.

When vinyl chloride is polymerised, we get polyvinyl chloride. It is represented as follows.



Homopolymers

When all the repeating units along a chain in a polymer are of the same type, is called homopolymer.

Copolymers

When the chains of a polymer are composed of two or different repeat units are termed as copolymers.

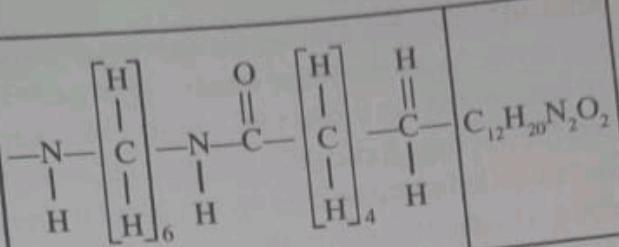
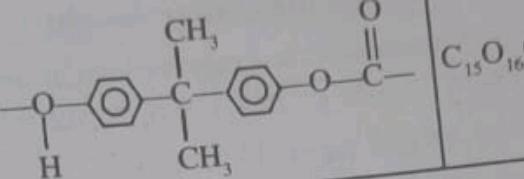
Examples are polyethylene vinyl acetate (PEVA), nitrile rubber and acrylonitrile butadiene styrene (ABS).

* The number of active bonds present in a monomer is termed as functionality. When an active bond that may react to form two covalent bonds with other monomers is termed as bifunctional when a monomer has three bonds to react with other monomers is termed as trifunctional.

A list of repeat units of some common polymeric material are given in table 7.2 below.

Table 7.2: A list of common polymers and their repeat units

No	Polymer	Repeat unit	Molecular formula of repeat unit
1	Polyethylene	$ \begin{array}{c} \text{H} \quad \text{H} \\ \quad \\ -\text{C}-\text{C}- \\ \quad \\ \text{H} \quad \text{H} \end{array} $	C ₂ H ₄
2	Polyvinyl chloride	$ \begin{array}{c} \text{H} \quad \text{H} \\ \quad \\ -\text{C}-\text{C}- \\ \quad \\ \text{H} \quad \text{Cl} \end{array} $	C ₂ H ₃ Cl
3	Polytetrafluoroethylene	$ \begin{array}{c} \text{F} \quad \text{F} \\ \quad \\ -\text{C}-\text{C}- \\ \quad \\ \text{F} \quad \text{F} \end{array} $	C ₂ F ₄
4	Polypropylene	$ \begin{array}{c} \text{H} \quad \text{H} \\ \quad \\ -\text{C}-\text{C}- \\ \quad \\ \text{H} \quad \text{CH}_3 \end{array} $	C ₃ H ₆
5	Polystyrene	$ \begin{array}{c} \text{H} \quad \text{H} \\ \quad \\ -\text{C}-\text{C}- \\ \quad \\ \text{H} \quad \text{C}_6\text{H}_5 \end{array} $	C ₈ H ₈
6	Polymethyl methacrylate	$ \begin{array}{c} \text{H} \quad \text{CH}_3 \\ \quad \\ \text{C}-\text{C} \\ \quad \\ \text{H} \quad \text{C}-\text{O}-\text{CH}_3 \\ \parallel \\ \text{O} \end{array} $	C ₅ O ₂ O ₈

7	Nylon 6,6	
8	Polycarbonate	

Molecular weight calculation

The molecular weight of a compound is calculated as follows:

Count the number of atoms of each element present in the compound and then multiply that number by the element's atomic weight. Adding all we get the molecular weight of the compound.

Example

Molecular weight of NaCl. It contains one atom of Na, whose atomic weight is 23 and one atom of Cl, whose atomic weight is 35.

$$\text{Molecular weight of NaCl} = 1 \times 23 + 1 \times 35 = 58.$$

Molecular weight of acetic acid CH_3COOH . It contains four hydrogen (Atwt 1) atoms two carbon atoms (Atwt 12) and 3 oxygen atoms (Atwt 16)

$$\begin{aligned}\text{Molecular weight} &= 4 \times 1 + 2 \times 12 + 2 \times 16 \\ &= 4 + 24 + 32 = 60.\end{aligned}$$

Here we will discuss how to calculate the molecular weight of polymers from its chain length. We found that polymers have very long chains. It is seen that polymers with large chains have large

molecular weights. During the process of polymerisation all chains will not grow to the same length. This means that polymer chains are distributed i.e. molecular weights are distributed so we have to find the average molecular weight. This can be done in two ways. One is called number average molecular weight, the other one is called weight average molecular weight.

Number average molecular weight

To find the number average molecular weight divide the chains into a series of size ranges. Let n_1 be the number of chains in the molecular weight range M'_1 and M'_2 .

So the molecular weight of that chain,

$$M_1 = n_1 \frac{(M'_1 + M'_2)}{2} = n_1 \bar{M}_1$$

where \bar{M}_1 is the average of the molecular range M'_1 and M'_2
similarly

Molecular weight of the second chain containing n_2 number in the molecular range M'_2 and M'_3 is

$$M_2 = n_2 (M'_2 + M'_3) = n_2 \bar{M}_2$$

and so on.

Therefore the total molecular weight of all the chains

$$M = M_1 + M_2 + \dots + M_n$$

i.e. $M = n_1 \bar{M}_1 + n_2 \bar{M}_2 + \dots + n_n \bar{M}_n$

∴ The number average molecular weight of the polymer,

$$\bar{M}_N = \frac{M}{N}$$

where N is the total number of chains, i.e. $N = n_1 + n_2 + n_3 + \dots$

i.e.

$$\bar{M}_N = \frac{M_1 + M_2 + M_3 + \dots}{N}$$

$$\bar{M}_N = \frac{n_1 \bar{M}_1 + n_2 \bar{M}_2 + n_3 \bar{M}_3 + \dots}{N}$$

$\frac{n_1}{N}$ is the first fractional number of chains denoted by x_1 similarly others.

Thus

i.e. $\bar{M}_N = x_1 \bar{M}_1 + x_2 \bar{M}_2 + \dots$

or $\bar{M}_N = \sum_{i=1}^n x_i \bar{M}_i$ (1)

and M_i

This is the expression for number average molecular weight.

Weight average molecular weight

We found that the number average molecular weight is defined on the basis of the number fraction of chains within each size range. **The weight average molecular weight is defined on the basis of weight fraction of molecules within various size ranges.**

∴ Weight average molecular weight, \bar{M}_w

$$\bar{M}_w = \sum_{i=1}^n w_i \bar{M}_i$$
 (2)

where w_i is the weight fraction of molecules within the same size interval and \bar{M}_i is the mean molecular weight within a size range.

Degree of polymerisation

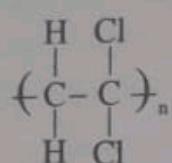
The degree of polymerisation (DP) is a term used to express the average chain size of a polymer. **Degree of polymerisation is**

defined as the ratio of the number average molecular weight (\bar{M}_n) and the repeat unit molecular weight m. (monomer)

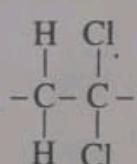
$$\text{i.e. } DP = \frac{\bar{M}_n}{m} \quad \dots \dots (3)$$

Repeat unit molecular weight is m

Consider a polyvinylchloride polymer:



In this repeating unit (monomer) is



It contains two carbon atoms three hydrogen atoms and one chlorine atom.

The molecular weight of repeating monomer

$$m = 2 \times \text{Atwt of C} + 3 \times \text{Atwt of H} + 1 \times \text{Atwt of Cl}$$

Example 1

The number average molecular weight of a polystyrene is 500,000 g/mol. Compute the degree polymerisation.

Solution

Polystyrene : $(\text{C}_8\text{H}_8)_n$

Molecular weight of repeat unit,

$$m = 8 \times \text{Atwt of C} + 8 \times \text{Atwt of H}$$

$$= 8 \times 12.01 + 8 \times 1.0078$$

$$\begin{aligned}
 &= 96.08 + 8.0624 \\
 &= 104.1424 \text{ g/mol}
 \end{aligned}$$

Using

$$DP = \frac{\bar{M}_n}{m} = \frac{500,000}{104.1424} = 4801.1$$

Example 2

Compute repeat unit molecular weights for the following
 (a) polytetrafluoroethylene (b) polymethyl methacrylate (c) nylon
 6,6 and (d) polyethylene terephthalate. ($C_{12}H_8O_4$)

Solution

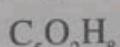
- a) The repeat unit of polytetrafluoroethylene is



Molecular weight of C_2F_4

$$\begin{aligned}
 &= 2 \times \text{Atwt of C} + 4 \times \text{Atwt of F} \\
 &= 2 \times 12.01 + 4 \times 18.9936 \\
 &= 100 \text{ g/mol}
 \end{aligned}$$

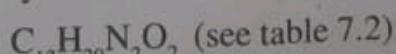
- b) The repeat unit of polymethyl methacrylate is



Molecular weight of $C_5O_2H_8$

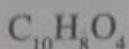
$$\begin{aligned}
 &= 5 \times \text{Atwt of C} + 2 \times \text{Atwt of O} + 8 \times \text{Atwt of H} \\
 &= 5 \times 12.01 + 2 \times 15.999 + 8 \times 1.0078 \\
 &= 60.05 + 31.998 + 8.0624 \\
 &= 100 \text{ g/mol}
 \end{aligned}$$

- c) The repeat unit of nylon 6,6 is



Molecular weight of nylon 6,6
 $= 12 \times \text{Atwt of C} + 20 \times \text{Atwt of H} +$
 $2 \times \text{Atwt of N}_2 + 2 \times \text{Atwt of O}$
 $= 12 \times 12.01 + 20 \times 1.0098 + 2 \times 14.0067 + 2 \times 15.499$
 $= 144.12 + 20.156 + 28.0134 + 31.998$
 $= 224.2874 \text{ g/mol}$

- d) The repeat unit of polyethylene terephthalate is



Molecular weight
 $= 10 \times \text{Atwt of C} + 8 \times \text{Atwt of H} + 4 \times \text{Atwt of O}$
 $= 10 \times 12.01 + 8 \times 1.0098 + 4 \times 15.999$
 $= 120.1 + 8.0624 + 63.996$
 $= 192.1584 \text{ g/mol}$

Example 3

Molecular weight data for a polytetrafluoroethylene material are given below. Compute (a) the number average molecular weight (b) the weight average molecular weight and (c) the degree of polymerisation.

Molecular weight range (g/mol)	x_i	w_i
10,000 - 20,000	0.03	0.01
20,000 - 30,000	0.09	0.04
30,000 - 40,000	0.15	0.11
40,000 - 50,000	0.25	0.23
50,000 - 60,000	0.22	0.24
60,000 - 70,000	0.14	0.18
70,000 - 80,000	0.08	0.12
80,000 - 90,000	0.04	0.07

Solution

a) The number average molecular weight

$$\bar{M}_N = \sum_{i=1}^{n=8} x_i \bar{M}_i$$

$$\bar{M}_N = x_1 \bar{M}_1 + x_2 \bar{M}_2 + x_3 \bar{M}_3 + \dots + x_8 \bar{M}_8 \quad \dots \quad (1)$$

$$\bar{M}_1 = \frac{10,000 + 20,000}{2} = 15,000$$

$$\bar{M}_2 = \frac{20,000 + 30,000}{2} = 25,000$$

$$\bar{M}_3 = \frac{30,000 + 40,000}{2} = 35,000$$

$$\bar{M}_4 = \frac{40,000 + 50,000}{2} = 45,000$$

$$\bar{M}_5 = \frac{50,000 + 60,000}{2} = 55,000$$

$$\bar{M}_6 = \frac{60,000 + 70,000}{2} = 65,000$$

$$\bar{M}_7 = \frac{70,000 + 80,000}{2} = 75,000$$

$$\bar{M}_8 = \frac{80,000 + 90,000}{2} = 85,000$$

$$\therefore \bar{M}_N = 10^3(0.45 + 2.25 + 5.25 + 11.25 + 12.1 + 9.1 + 6 + 3.4)$$

$$= 10^3 \times 49.8$$

$$= 49800 \text{ g/mol}$$

b) The weight average molecular weight,

$$\bar{M}_w = \sum_{i=1}^{n=8} w_i \bar{M}_i \quad \dots \dots (2)$$

$$w_1 = 0.01, \quad \bar{M}_1 = 15,000$$

$$w_2 = 0.04, \quad \bar{M}_2 = 25,000$$

$$w_3 = 0.11, \quad \bar{M}_3 = 35,000$$

$$w_4 = 0.23, \quad \bar{M}_4 = 45,000$$

$$w_5 = 0.24, \quad \bar{M}_5 = 55,000$$

$$w_6 = 0.18, \quad \bar{M}_6 = 65,000$$

$$w_7 = 0.12, \quad \bar{M}_7 = 75,000$$

$$w_8 = 0.07, \quad \bar{M}_8 = 85,000$$

Putting these values in eq (2), we get

$$\begin{aligned} \bar{M}_w &= 0.01 \times 15 \times 10^3 + 0.04 \times 25 \times 10^3 + 0.11 \times 35 \times 10^3 + \\ &\quad 0.23 \times 45 \times 10^3 + 0.24 \times 55 \times 10^3 + 0.18 \times 65 \times 10^3 + \\ &\quad 0.12 \times 75 \times 10^3 + 0.07 \times 85 \times 10^3 \end{aligned}$$

$$\bar{M}_w = 10^3(0.15 + 1 + 3.85 + 10.35 + 13.2 + 15.6 + 9 + 5.95)$$

$$\bar{M}_w = 59.1 \times 10^3 \text{ g/mol}$$

c) Degree of polymerisation

$$DP = \frac{\bar{M}_N}{m} \quad \dots \dots (3)$$

The given polymer is polytetrafluoroethylene is



The molecular weight of tetrafluoroethylene,

$$m = 2 \text{ Atwt of C} + 4 \text{ Atwt of F}$$

$$= 2 \times 2.01 + 4 \times 18.9984$$

$$= 24.02 + 75.9936 = 100$$

$$\therefore DP = \frac{49,800}{100} = 498$$

Example 4

From the given data table for polyvinyl chloride compute (a) the number average molecular weight (b) the degree of polymerisation and (c) the weight average molecular weight.

Molecular weight range (g/mol)	x_i	w_i
5,000 - 10,000	0.05	0.02
10,000 - 15,000	0.16	0.10
15,000 - 20,000	0.22	0.18
20,000 - 25,000	0.27	0.29
25,000 - 30,000	0.20	0.26
30,000 - 35,000	0.08	0.13
35,000 - 40,000	0.02	0.02

Solution

- a) The number average molecular weight,

$$\bar{M}_N = \sum_{i=1}^7 x_i \bar{M}_i \quad \dots\dots (1)$$

$$x_1 = 0.05, \bar{M}_1 = \frac{5,000 + 10,000}{2} = 7,500$$

$$x_2 = 0.16, \bar{M}_2 = \frac{10,000 + 15,000}{2} = 12,500$$

$$x_3 = 0.22, \bar{M}_3 = \frac{15,000 + 20,000}{2} = 17,500$$

$$x_4 = 0.27, \bar{M}_4 = \frac{20,000 + 25,000}{2} = 22,500$$

$$x_5 = 0.20, \bar{M}_5 = \frac{25,000 + 30,000}{2} = 27,500$$

$$x_6 = 0.08, \bar{M}_6 = \frac{30,000 + 35,000}{2} = 32,500$$

$$x_7 = 0.02, \bar{M}_7 = \frac{35,000 + 40,000}{2} = 37,500$$

$$\begin{aligned}\bar{M}_N &= 0.05 \times 7,500 + 0.16 \times 12,500 + 0.22 \times 17,500 \\ &\quad + 0.27 \times 22,500 + 0.20 \times 27,500 + 0.08 \times 32,500 \\ &\quad + 0.02 \times 37,500\end{aligned}$$

$$\bar{M}_N = 375 + 2000 + 3850 + 6075 + 5500 + 2600 + 750$$

$$\bar{M}_N = 21,150 \text{ g/mol}$$

- b) The degree of polymerisation, $DP = \frac{\bar{M}_N}{m}$ where m is the molecular weight of the repeating unit i.e. vinylchloride C_2H_3Cl .

$$\begin{aligned}
 \therefore \text{Molecular weight of } C_2H_3Cl \\
 &= 2 \times \text{Atwt of C} + 3 \times \text{Atwt of H} + 1 \times \text{Atwt of Cl} \\
 &= 2 \times 12.01 + 3 \times 1.01 + 1 \times 35.45 \\
 &= 24.02 + 3.03 + 35.45 = 62.5 \text{ g/mol}
 \end{aligned}$$

$$\therefore DP = \frac{21,150}{62.50} = 338.4$$

$$\bar{M}_w = w_1 \bar{M}_1 + w_2 \bar{M}_2 + w_3 \bar{M}_3 + w_4 \bar{M}_4$$

$$+ w_5 \bar{M}_5 + w_6 \bar{M}_6 + w_7 \bar{M}_7$$

$$\begin{aligned}
 \bar{M}_w &= 0.02 \times 7,500 + 0.10 \times 12,500 + 0.18 \times 17,500 \\
 &\quad + 0.29 \times 22,500 + 0.26 \times 27,500 + 0.13 \times 32,500 \\
 &\quad + 0.02 \times 37,500
 \end{aligned}$$

$$\bar{M}_w = 150 + 1250 + 3150 + 6525 + 7150 + 4225 + 750$$

$$\bar{M}_w = 23,200 \text{ g/mol.}$$

Molecular shape

So far we considered polymer molecules as lines, neglecting the zigzag arrangements of the backbone atoms (see figure 7.6). The single chain bonds are capable of rotating and bending in three dimensions. We found that the angle between the singly bonded carbon atom is 109° , not 180° . In actual 3D, situation is different. Consider the chain atoms in figure 7.7(a). In this, a third carbon atom may lie at any point on the cone of revolution and still subtend an angle of about 109° with the bond between the other two atoms. When successive such atoms are positioned we get a straight

chain as shown in figure 7.7(b). On the other hand, chain bending and twisting are possible when there is a rotation of the chain atoms into other positions as shown in figure 7.7(c).

Figure 7.7(a), (b) and (c). Showing how polymer chain shape is influenced by the positioning of backbone carbon atoms. The above discussion shows that a single chain molecule composed of many chain atoms might assume a shape of the form given in figure 7.8. This chain having large number of bends, twists and kinks. The end to end distance of the polymer chain 'r' is also indicated.



Figure 7.7(a)

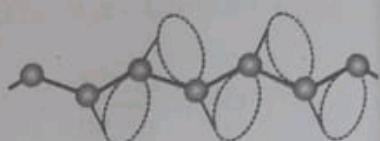


Figure 7.7(b)

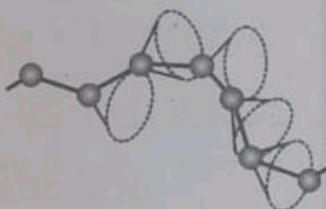


Figure 7.7(c)

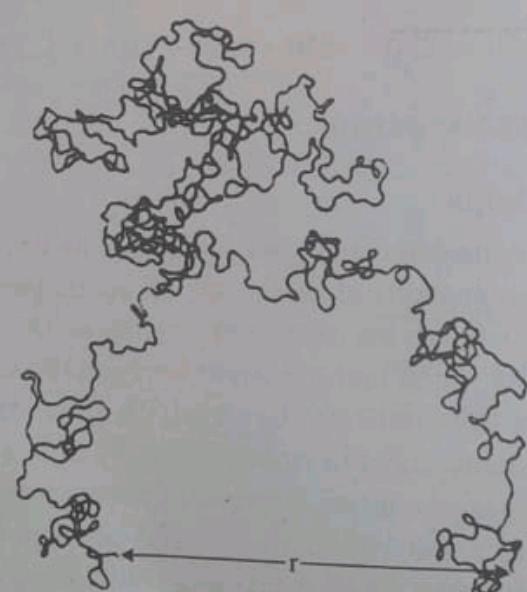


Figure 7.8

The above number of monomer units leads to neighbouring chain. These randomised for a number of elastic extension.

Some of the depend on the applied stresses upon the repeating carbon double bonds of large size. For example see table 7.2, C polyethylene ch

Molecular structure

The physical molecular weight Modern polymers control the structural properties. There are

1. linear polymers
2. branched polymers
3. cross linked network polymers
4. various isotactic polymers

Linear polymers

The above discussion shows that polymers consists of large number of molecular chains, each of which may bend, coil and kink leads to extensive intertwining and entanglement of neighbouring chain molecules is analogous to a tangled fishing line. These random coils and molecular entanglements are responsible for a number of important properties of polymers such as elastic extensions shown by the rubber materials.

Some of the mechanical and thermal properties of polymers depend on the ability of chain segments for rotation in response to applied stresses or thermal vibrations. Rotational ability depends upon the repeat unit structure. For example a chain which has a carbon double bond ($C = C$) is rotationally rigid. Also the presence of large side group of atoms restricts rotational movement. For example polystyrene molecules which has a phenyl side group (see table 7.2, (5)) are more resistant to rotational motion than the polyethylene chains which don't have side group.

Molecular structure

The physical properties of polymers depend upon two factors molecular weights and their structure of the molecular chains. Modern polymer synthesis techniques revealed that we can control the structure of molecular chains thereby changing their properties. There are five types of molecular structures. They are

1. linear polymers
2. branched polymers
3. cross linked polymers
4. network polymers and
5. various isomeric configurations.

I. Linear polymers

Linear polymers are those in which the repeat units are

joined end to end in single chains.

These long chains are flexible and may be thought of as a mass of spaghetti, as represented schematically in figure 7.9(a).

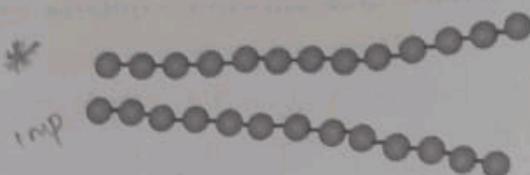


Figure 7.9(a): Linear polymers

In the figure 7.9(a), each circle represents a repeat unit. In linear polymers there may be extensive vander Waals and hydrogen bonding between the chains. Polyethylene, polyvinyl chloride, polystyrene, polymethyl methacrylate, nylon and the fluorocarbons are linear chain polymers. See also table 7.2.

2. Branched polymers

Branched polymers are those in which side branch chains are connected to the main linear chains.

This is depicted schematically in figure 7.9(b) given below.

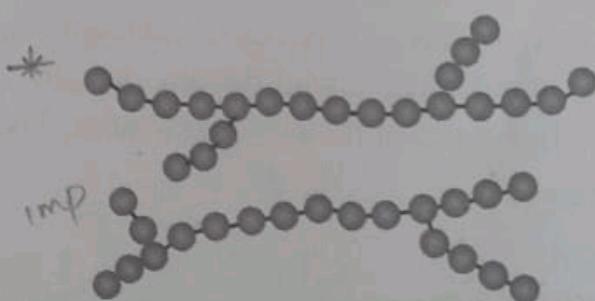


Figure 7.9(b): Branched chain polymers

The branches are considered to be part of the main chain molecule, may result from side reactions that occur during synthesis of the polymer. It is due to these branches, the chain packing effi-

ciency is reduced which results in a lowering of the polymer density. The polymers that form linear structures may also be branched. For example high density polyethylene is basically a linear polymer whereas low density polyethylene contains short chain branches.

3. Cross linked polymers

Cross linked polymers are polymers in which adjacent linear chains are joined one to another at various positions by covalent bonds.

Cross linked polymers are schematically represented in figure 7.9(c) given below.

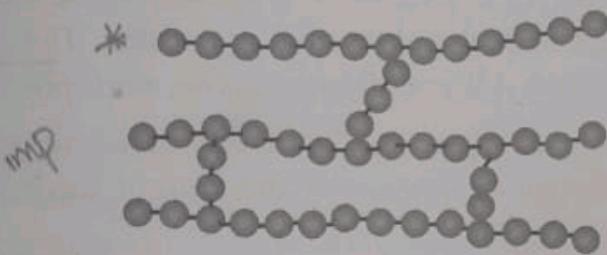


Figure 7.9(c): Cross linked polymers

The cross linking process in a polymer occurs either during synthesis or by a non-reversible chemical reactions. The cross linking is accomplished by additive atoms or molecules that are covalently bonded to the chains. Many of the rubber elastic materials are cross linked in rubbers. This process is called vulcanization.

4. Network polymers

Network polymers are polymers in which the multifunctional monomers (basic repeat unit) forming three or four active covalent bonds results in 3 dimensional networks.

This is shown in figure 7.9(d) below.

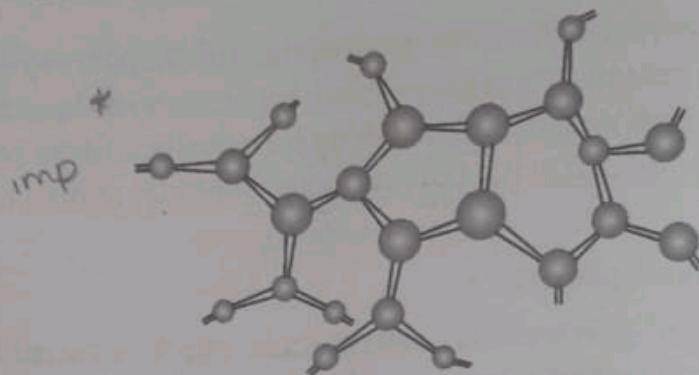


Figure 7.9(d): Network polymers

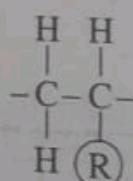
It may be noted that a polymer actually a highly cross linked may also be considered as a network polymer. These materials have distinctive mechanical and thermal properties. The epoxies polyurethanes and phenol formaldehyde are network polymers.

Polymers are not usually of one distinctive structure type. For example a predominantly linear polymer might have limited branching and cross linking.

Molecular configurations

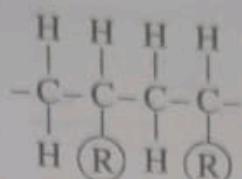
Configuration refers to arrangements of units along the axis of the chain.

Polymers having more than one side atom or group of atoms bounded to the main chain, the regularity and symmetry of the side group arrangement can significantly influence the properties of the polymers. To understand this consider the repeat unit



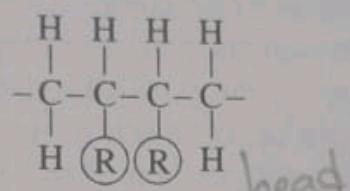
where R represents an atom or side group other than hydrogen (e.g., Cl, CH₃ etc.) There are two possible arrangements of R. In

one arrangement the R side groups of successive repeats are bound to alternate carbon atoms as follows:



This arrangement is termed as head to tail configuration.

In the second arrangement R groups are bound to adjacent carbon atoms as shown below:



This arrangement is termed as head to tail configuration. In this configuration often a polar repulsion occurs between the two adjacent R groups. In most polymers, the head to tail configuration predominates.

Isomerism in polymers

When different atomic configurations are for the same composition of polymers, they are said to be isomers of the polymer.

Isomers are further classified into several subclasses. Two of them are stereoisomerism and geometrical isomerism.

Stereoisomerism

Stereoisomerism also called as spatial isomerism is a form of isomerism in which molecules have the same molecular formula and sequence of bonded atom but differ in the three-dimensional orientations of their atoms in space.

Stereoisomers can be subdivided into two; one is called isotactic and the other is called syndiotactic.

Tacticity is a term used to describe the way pendant groups (R) on a polymer chain arranged on a polymer backbone. The tacticity of a polymer is determined by what side of the polymer chain the pendant groups are on. This relative position can have dramatic effects on the physical properties of the polymer.

When a monomer adds to the end of the polymer chain, the monomer can either join the pendant group on the same side as all of the other pendant groups or it can join the pendant group on the side away from the pendant group. If the monomer adds to the polymer back bone with the pendant group (R) on the same as the previous pendant group this is called isotactic configuration. If the monomer adds to the opposite side of the polymer backbone it is called syndiotactic configuration. If there is no order to the way the pendant group adds (random) the polymer is said to be atactic and the corresponding configuration is called atactic configuration. Isotactic, syndiotactic and atactic configurations are (2 and 3 D) given below in figure 7.10 (a, b and c)

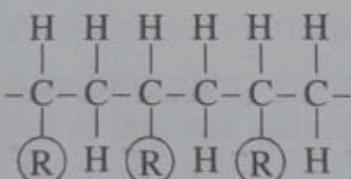
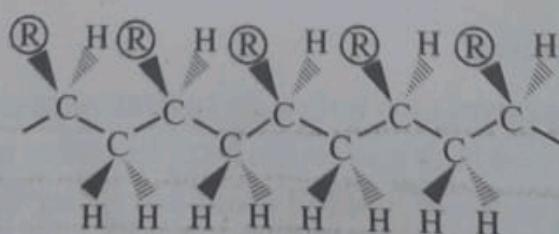


Figure 7.10(a): Two dimensional linear 2D isotactic configuration



The three dimensional isotactic configuration

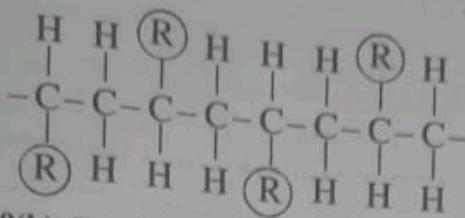
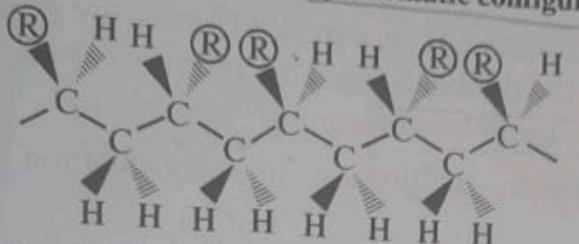
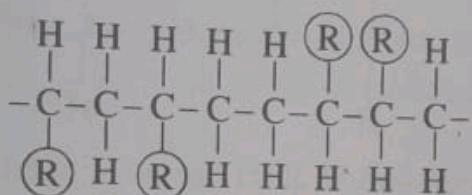


Figure 7.10(b): The linear 2D syndiotactic configuration

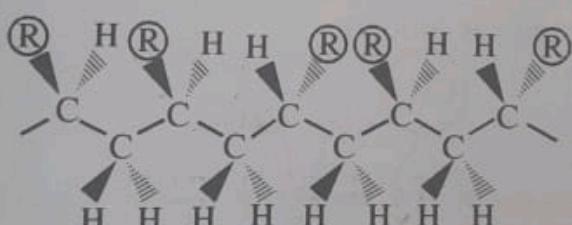


The three dimensional syndiotactic configuration



(no order)

Figure 7.10(c): The linear 2D atactic configuration

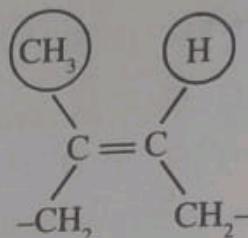


The three dimensional atactic configuration

Geometrical isomerism

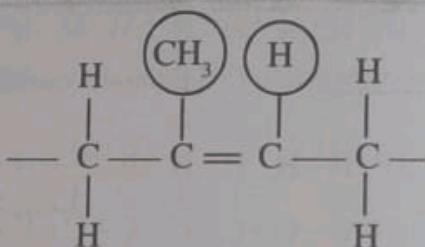
Geometrical isomerism is a form of isomerism describing the orientation of functional groups within a molecule.

In general geometrical isomers contain double bonds which cannot rotate like single bond atoms. The rotation is restricted also by ring structure. For example consider the isoprene repeat unit having the structure.

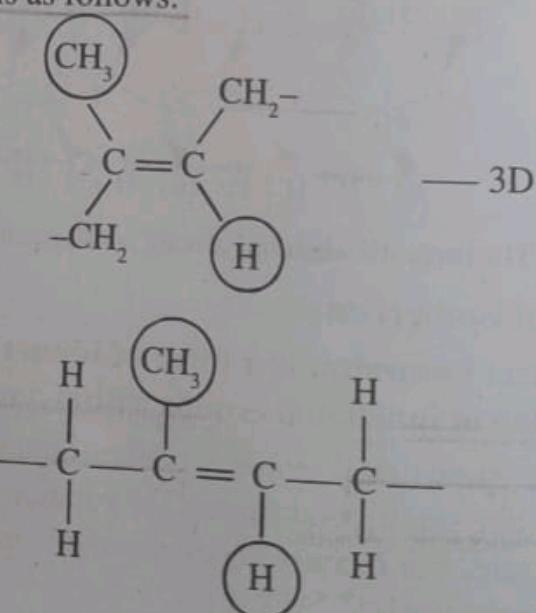


In this structure CH_3 group and H atom are positioned on the same side of the double bond. This is termed as cis structure. The prefix cis is a Latin word meaning “this side of”.

For cis-isoprene the linear chain representation is as follows:



If the CH_3 group and H atom are positioned on the opposite sides of the double bond, it is termed as trans structure. The prefix trans is a Latin word meaning “the other side of”. The structure of trans isoprene is as follows:



This is the linear trans structure of isoprene.

Trans polyisoprene is sometimes called gutta percha. This has properties distinctly different from natural rubber as a result of its configurational alteration.

It may be noted that conversion of trans to cis or vice versa is not possible by a simple chain bond rotation because the chain double bond is extremely rigid.

Summarising the subheading molecular weight (size), molecular shape, molecular structure and molecular configurations, we can say the following: Molecular characteristics of polymers is given by four factors. They are

1. repeat unit configuration
2. size (molecular weight)
3. shape (chain twisting coiling and bending) and

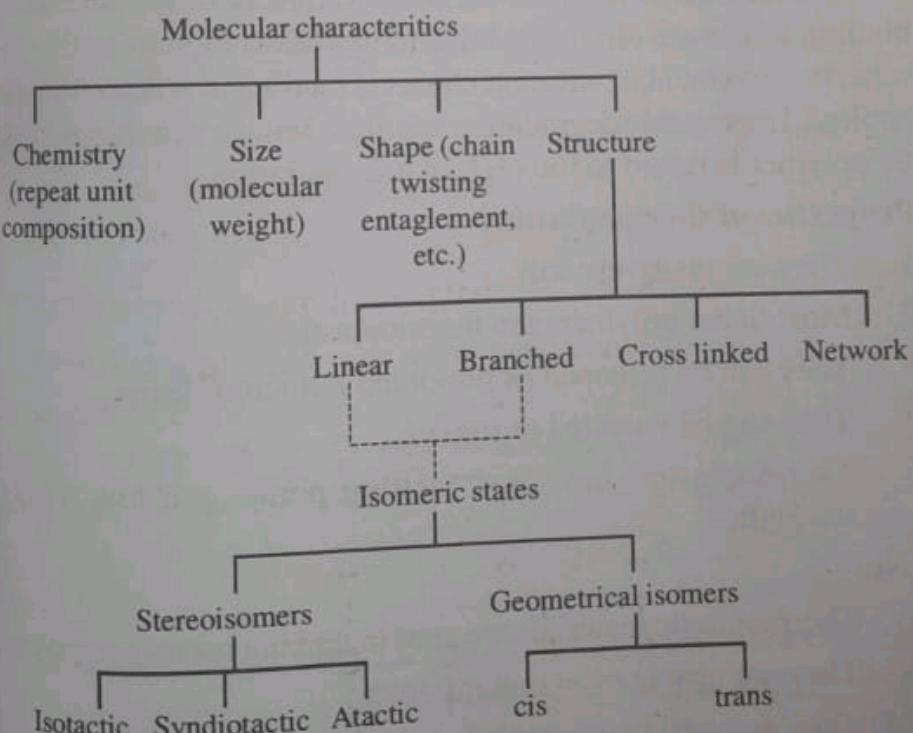


Figure 7.11: Taxonomy chart

4. molecular structure (linear, branched, cross linked and network structures are possible in addition to several isomeric configurations such as isotactic, syndiotactic, atactic, cis and trans. The molecular characteristics taxonomy chart is given in figure 7.11.

→ Thermoplastic and thermosetting polymers

Thermoplastics

Thermoplastics are polymers that can be softened through heating before being processed then left to cool and harden.

Once cooled, they show no changes in chemical properties, meaning they can be remelted and re-used several times.

Polyester, polypropylene, polystrene, teflon, acrylic, polyvinyl chloride etc. are thermoplastic polymers or called thermoplastics.

On a molecular level, as the temperature is raised secondary binding forces are diminished due to increased motion so that the relative movement of adjacent chains is facilitated when a stress is applied. Irreversible degradation results when molten thermoplastic polymer is raised to too high of a temperature.



Properties of thermoplastics

1. They are relatively soft
2. Most linear polymers are thermoplastics.
3. They can be reshaped or remolded numerous times.
4. They can be recycled or reused.
5. Thermoplastics have low melting points and low tensile strength.

* Uses

1. Thermoplastic materials are used in making sports equipment.
2. They are also used in making toys.
3. They are used in automobile parts.

4. They are used in making CDs and DVDs.
 5. Containers like shampoo bottles, drinking bottles and food storage containers are made up of thermoplastic polymers.
- Note: Thermoplastics are fabricated by the simultaneous application of heat and pressure.

Thermosetting polymers

Thermoset is a polymer material that strengthens when heated but cannot be remoulded or heated after initial formation.

Epoxy, silicone, polyurethane, phenolic, vulcanised rubbers, polyester resins are examples of thermosetting polymers or called also thermosets.

Properties

1. They become permanently hard during their formation.
2. They are stronger than thermoplastics and have better dimensional stability.
3. They have high melting point and high tensile strength.
4. Thermosets are network polymers.
5. They cannot be recycled or remoulded. (reshaped)

Why thermosets are hard?

Thermosets are network polymers. Network polymers have covalent cross links between adjacent molecular chains. During heating these bonds anchor the chains together to resist the vibrational and rotational chain molecules at high temperatures. Thus materials do not soften when heated.

Uses

1. Thermostats are used for producing electrical goods such as circuit breakers as well as components such as panels and insulators.

2. They are used for manufacturing construction equipment panels.
3. Thermosets are used for manufacturing heat shields.
4. They are also used in agricultural feeding troughs, motor components and disc break pistons.

Stress-strain behaviour of polymers

The mechanical properties of polymers such as strength, toughness, hardness, hardenability, brittleness, malleability, ductility, creep and slip, resilience, tactique etc. are specified with the same parameters that are used for metals - i.e. modulus of elasticity, yield strengths, and tensile strengths. These mechanical parameters are ascertained by simple stress-strain test. But the mechanical properties of polymers are highly sensitive to the strain rate, the temperature and the nature of the environment (the presence of water, oxygen, organic solvents etc.). Considering these factors some modifications with regard to stress-strain behaviour of metals are required when it is applied to polymers.

There are three different types of stress-strain behaviour observed for polymers. They are

1. the stress-strain behaviour of brittle polymer
2. the stress-strain behaviour of plastic polymer and
3. the stress-strain behaviour of elastic polymers.

The stress-strain behaviour of brittle polymer

The stress-strain behaviour of a brittle polymer is shown in figure 7.12 below.

The graph shows that a very little strain is produced in the brittle polymer when subjected to stress of the order of mega pascals. The point marked as (x) indicates the brittle point. Moreover the stress-strain relation is linear.

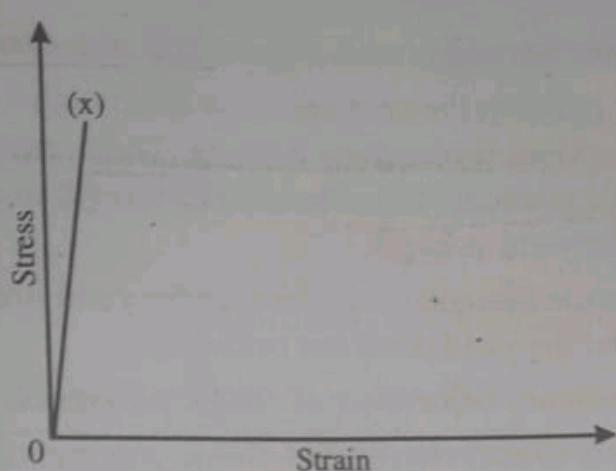


Figure 7.12: The stress-strain behaviour of brittle polymer

The stress-strain behaviour of plastic polymer

The stress-strain behaviour of plastic polymer is given in figure 7.13 below.

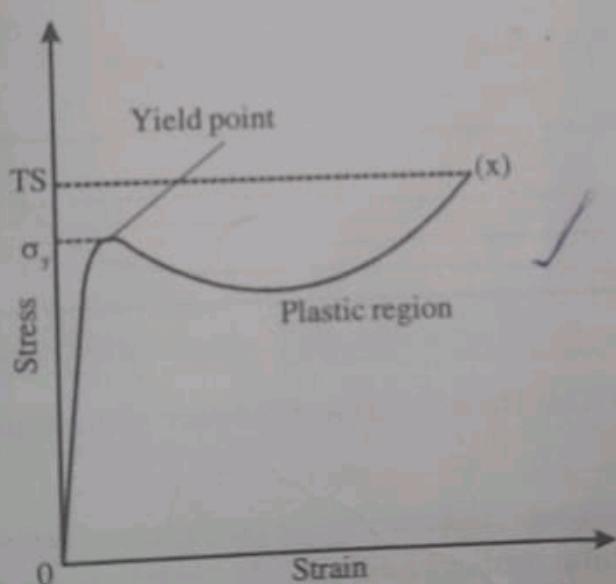


Figure 7.13: The stress-strain behaviour of plastic polymer

The behaviour of plastic polymer is similar to that of metals. Initially there is an elastic region where stress is directly proportional to strain. The maximum point on the curve gives yield point

which is just beyond elastic region. The stress corresponding to maximum point on the curve give yield strength (σ_y). The point marked as (x) corresponds to fracture. The corresponding stress gives tensile strength (TS). The tensile strength may be greater or less than the yield strength.

If the tensile strength is smaller than the yield strength the curve ends beyond the yield point but below it.

The stress-strain behaviour of elastic polymers

The stress-strain behaviour of elastic polymers is given in figure 7.14.

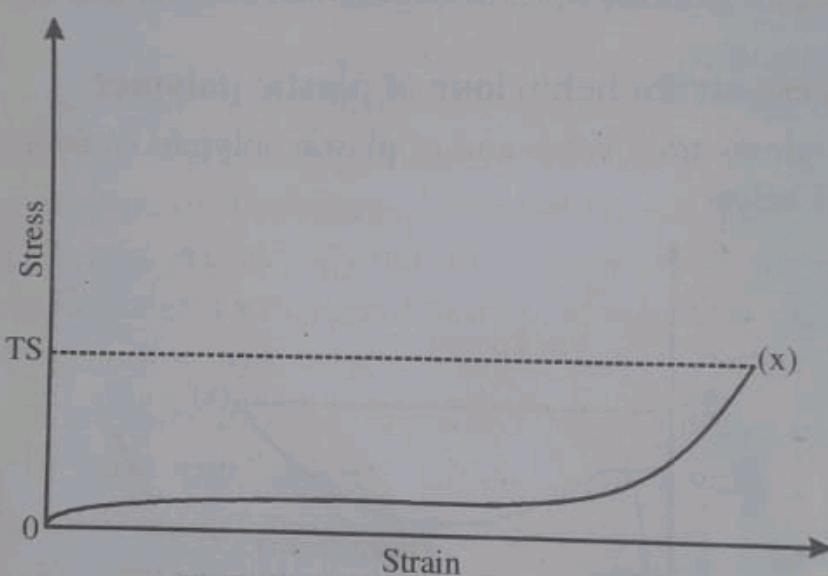


Figure 7.14: The stress-strain behaviour of elastic polymer

The deformation displayed by the curve is totally elastic – Elastic polymers exhibit rubber like elasticity, which means that large recoverable strains produced for low stress levels. These polymers are termed as elastomers. The highest point marked on the curve as (x) gives the breaking point. The corresponding stress gives tensile strength (TS).

The influence of temperature on the stress-strain behaviour

The stress-strain behaviour of polymers are strongly influenced by variation in temperature. The stress-strain behaviour of a particular polymer is shown at different temperatures in figure 7.15.

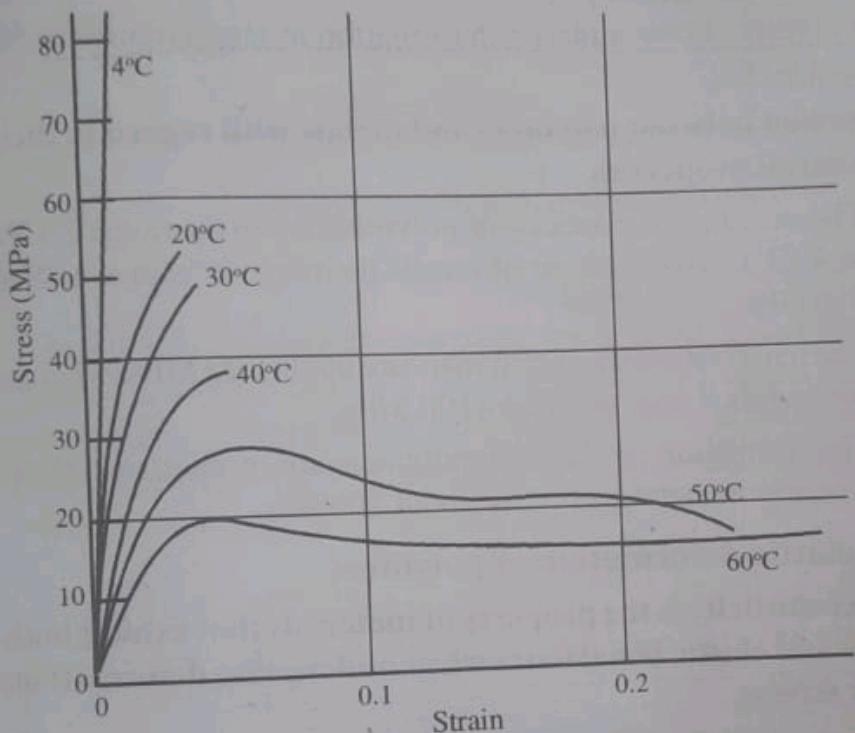


Figure 7.15: Stress-strain graph at different temperatures

From the graph the following things may be observed.

- When temperature increases its elastic modulus $\left(\frac{\text{stress}}{\text{strain}} \right)$ decreases, since the slope of the graph $\left(\frac{\text{stress}}{\text{strain}} \right)$ decreases.
- The tensile strength (TS) of the polymer also decreases as temperature increases. Tensile strength is the maximum stress corresponding to the end point of the curve.

3. The ductility of the polymer is largest at low temperature. Ductility is the ability of a material to get stretched into wire by pulling. Ductility indicates that how easily a material gets deformed under tensile stress. With rise in temperature the ductility increases.
4. Polymer shows a plastic deformation at temperatures at 50° and 60°C .

Distinction between polymers and metals with regard to their mechanical properties

1. The modulus of elasticity of polymers are in the range 7 MPa to 4 GPa, whereas that of metals the range is between 48 to 410 GPa.
2. The tensile strength of polymers are about 100 MPa, whereas for metals it may go up to 4100 MPa.
3. The elongation produced in polymers are more than 1000%, whereas in metals it is only about 100%.

Viscoelastic deformation of polymers

Viscoelasticity is the property of materials that exhibit both viscous and elastic behaviours when undergoing deformation, (under stress).

The elastic deformation is instantaneous and the viscous drag takes time. After the load removal, the elastic deformation is immediately reversible and recoverable, whereas the viscous drag is not reversible.

For elastic deformation the load-time graph and the corresponding strain-time graph is given

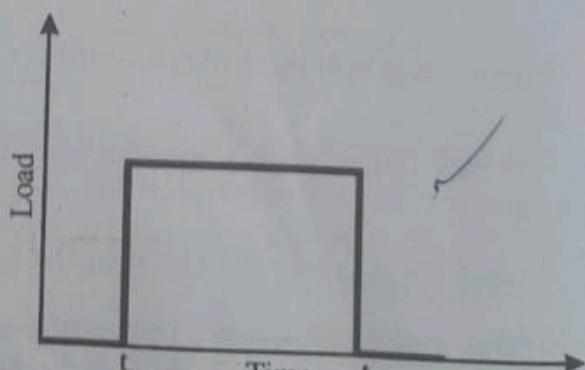


Figure 7.16(a)

in figures 7.16(a) and 7.16(b). Here the load is applied instantaneously at time t_a and release at t_r .

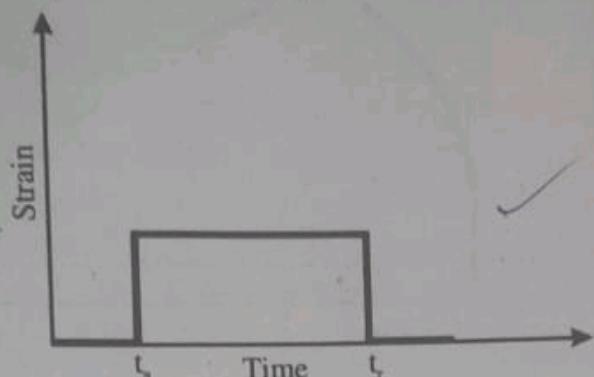


Figure 7.16(b)

For totally viscous behaviour the strain is not instantaneous in response to an applied stress the deformation is delayed or dependant on time. This deformation is not reversible or completely recovered after the stress is released. The strain-time behaviour of totally viscous material is given in figure 7.17.

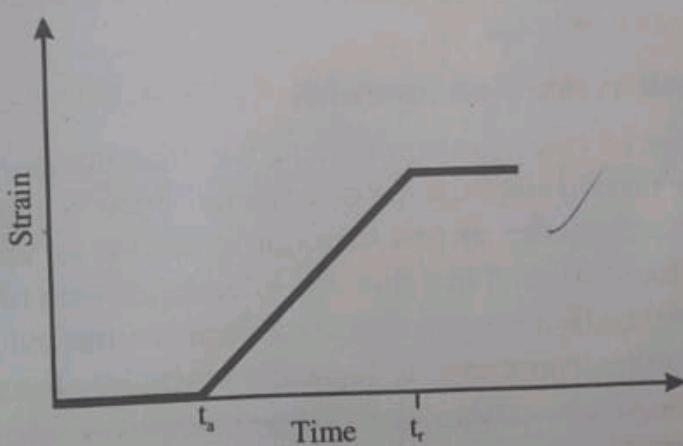


Figure 7.17

For a viscoelastic material the strain-time behaviour in response to load given in figure 7.16(a) is given in figure 7.18.

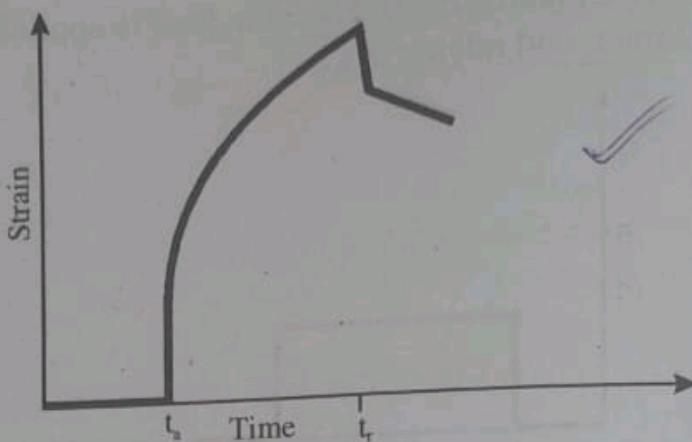


Figure 7.18

One familiar polymer that shows viscoelastic nature is silicone. This is known as "silly putty". When it is rolled into a ball and dropped onto a horizontal surface it bounces elasticity, the rate of deformation during the bounce is very rapid. If this ball is pulled under tension with a gradually increasing applied stress the material elongates or flows like highly viscous liquid. For all viscoelastic materials the rate of strain determines whether it is due to elasticity or viscosity or both.

Viscoelastic relaxation modulus

In the case of viscoelastic polymers, the stress necessary to produce a given strain is a function of time. i.e. stress is a function of time. So the elasticity of this material is termed as viscoelastic modulus. But it is found that this stress decreases with time due to molecular relaxation process that takes place within the polymer. So we introduce a new term to represent elasticity of viscoelastic polymer termed as viscoelastic relaxation modulus denoted by $E_r(t)$. It is defined as the ratio between time dependent stress $\sigma(t)$ and the strain ϵ_0 .

i.e.

$$E_r(t) = \frac{\sigma(t)}{\epsilon_0} \quad \dots\dots (4)$$

This is measured at constant temperature since change in temperature influences the stress-strain behaviour of the polymer.

Viscoelastic creep

When a viscoelastic material is subjected to a constant stress it experiences time dependent increase in strain. This phenomenon is called viscoelastic creep. The associated modulus is called viscoelastic creep modulus $E_c(t)$. **It is defined as the ratio between constant stress to the time dependent strain keeping temperature constant.**

i.e.

$$E_c(t) = \frac{\sigma_0}{\epsilon(t)}$$



It may also be noted that $E_c(t)$ is also temperature dependent

Note: Creep is the property of a material which indicates the tendency of material to move slowly and deform permanently under the influence of external mechanical stress.

UNIVERSITY MODEL QUESTIONS

Section A

(Answer questions in two or three sentences)

Short answer questions

1. Write down the four names of polymorphs of carbon.
2. Draw the unit cell for diamond cubic crystal.
3. Write down any two properties of diamond.
4. Write down two applications diamond thin film.
5. Give any two uses of graphite.
6. Draw the structure of graphite.
7. Draw the structure of a C_{60} molecule.
8. Give the properties of fullerenes.
9. What are carbon nanotubes?

10. Explain briefly about fullerene.
11. What are the composites of polymers?
12. Give a schematic representation of covalent bonding in a molecule of methane.
13. Give the structural formula of the following.
 - (a) CH_4 (b) C_2H_4 and (c) C_2H_2
14. Distinguish between the saturated and unsaturated hydrocarbons.
15. What types of bonding are present in paraffin family?
16. Why the family members of paraffin have low melting and boiling points?
17. What are isomers?
18. Which are the two isomers of butane?
19. Give the structural formula of normal and isobutane.
20. Why polymers are referred to as macromolecules?
21. How does a polymer molecule form?
22. What are homopolymers?
23. What are copolymers?
24. Give two examples of copolymers.
25. What is meant by functionality with regard to copolymers?
26. Explain the terms bifunctional and trifunctional.
27. What is meant by number average molecular weight?
28. What is meant by weight average molecular weight?
29. What is meant by degree of polarisation?
30. What is the information given by molecular shape?
31. What are the two factors that give physical properties of polymers?
32. What are linear polymers?
33. What are branched polymers?
34. What are cross-linked polymers?
35. What are network polymers?
36. What is meant by isomerism in polymers?

37. Classify stereoisomers.
38. What is meant by isotactic configuration?
39. What is meant by syndio tactic configuration?
40. What is meant by atactic configuration?
41. What is meant by geometrical isomerism?
42. What are thermoplastics?
43. Give three examples of thermoplastic polymers.
44. What are thermosetting polymers?
45. Why thermosets are hard?
46. What is meant by viscoelasticity?
47. Define viscoelastic relaxation modulus.
48. Define viscoelastic creep modulus.
49. Draw the strain-time graph of viscous deformation.
50. Draw the strain-time graph of viscoelastic deformation.

Section B

(Answer questions in a paragraph of about
half a page to one page)

Paragraph / Problem type

1. Briefly explain diamond as one of the polymorphic forms of carbon.
2. What are the properties of diamond?
3. What are the uses of diamond?
4. How diamond thin film is fabricated?
5. Give a brief account of the structure of graphite.
6. What are the properties of graphite?
7. What is fullerene?
8. Give any two uses of carbon nanotubes.
9. Give examples of natural polymers.
10. Explain the carbon chain polymers.
11. Explain briefly the formation of polyethylene.
12. How do we calculate the molecular weight of a compound?

13. Distinguish between the number average and weight average molecular weight.
14. How do we calculate the number average molecular weight?
15. How do we calculate the weight average molecular weight?
16. Give a brief account of molecular shape.
17. Distinguish between stereoisomerism and geometrical isomerism.
18. Write a brief note on molecular configuration.
19. Explain geometrical isomerism taking isoprene as example.
20. Distinguish between cis and trans isomers.
21. What are the factors on which molecular characteristics of polymers depend?
22. What are the properties of thermoplastics?
23. What are the uses of thermoplastics?
24. What are the uses of thermostats?
25. What is the importance of stress-strain behaviour of polymers?
26. Write down the three different types of stress-strain behaviour of polymers.
27. Give a brief account of stress-strain behaviour of brittle polymer.
28. Explain briefly the stress-strain behaviour of plastic polymer.
29. Explain the stress-strain behaviour of elastic polymer briefly.
30. Give a brief account of the influence of temperature on the stress-strain behaviour of polymers.
31. Distinguish between metals and polymers with regard to their mechanical properties.
32. Distinguish between elastic and viscous deformations.